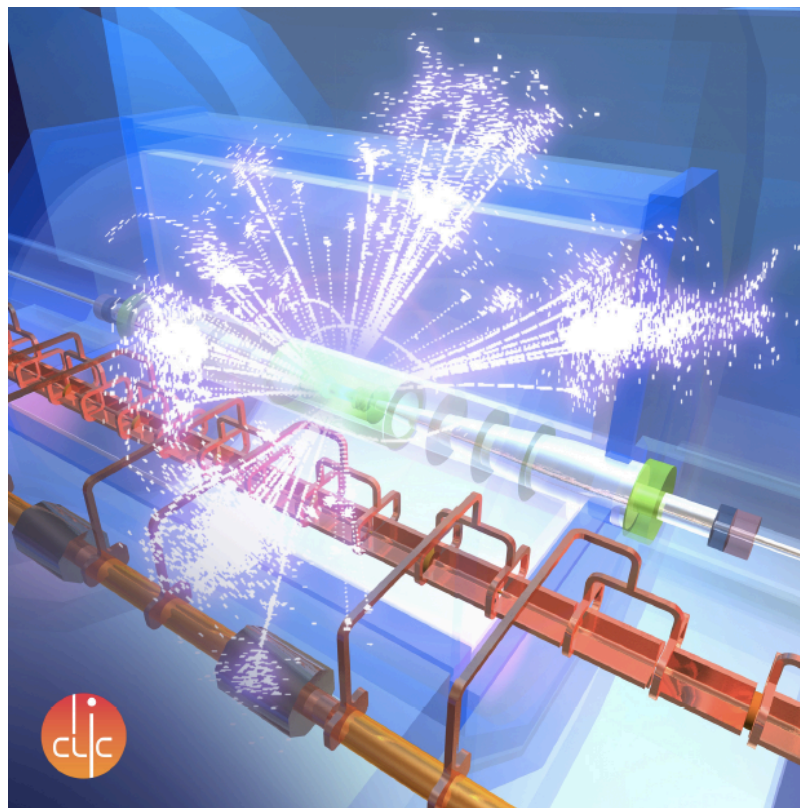


CLIC capabilities for precision electroweak physics



Lucie Linssen, CERN
on behalf of the CLIC detector and physics study

Lucie Linssen, EWprecision, BNL-Snowmass, 5 April 2013

Outline, references



Outline

- CLIC machine, physics, energy staging
- Top
- SM Higgs, Higgs multiplet, Higgs compositeness
- Z' , contact interactions and other physics reach
- Summary and outlook

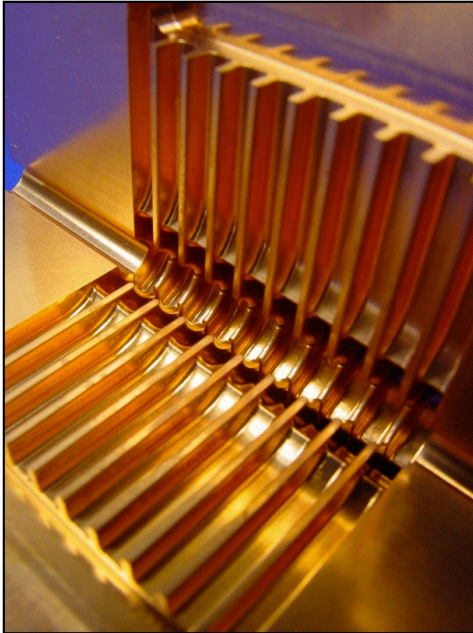
References

- CLIC CDR (#1), A Multi-TeV Linear Collider based on CLIC Technology, <https://edms.cern.ch/document/1234244/>
- CLIC CDR (#2), Physics and Detectors at CLIC, arXiv:1202.5904
- CLIC CDR (#3), The CLIC Programme: towards a staged e^+e^- Linear Collider exploring the Terascale, arXiv:1209.2543
- Brau et al., the physics case for an e^+e^- linear collider, arXiv:1210.0202
- D. Dannheim et al., CLIC e^+e^- linear collider studies, Input to the Snowmass process 2013 (submitted to the accelerator WG for Snowmass)

CLIC in just a few words



CLIC is the most mature option for a multi-TeV scale future e^+e^- collider



- 2-beam acceleration scheme at room temperature
- Gradient 100 MV/m \Rightarrow \sqrt{s} up to 3 TeV
- Staging scenario ~ 350 GeV to 3 TeV
- High luminosity (a few 10^{34} $\text{cm}^{-2}\text{s}^{-1}$)

focus is on energy frontier reach !

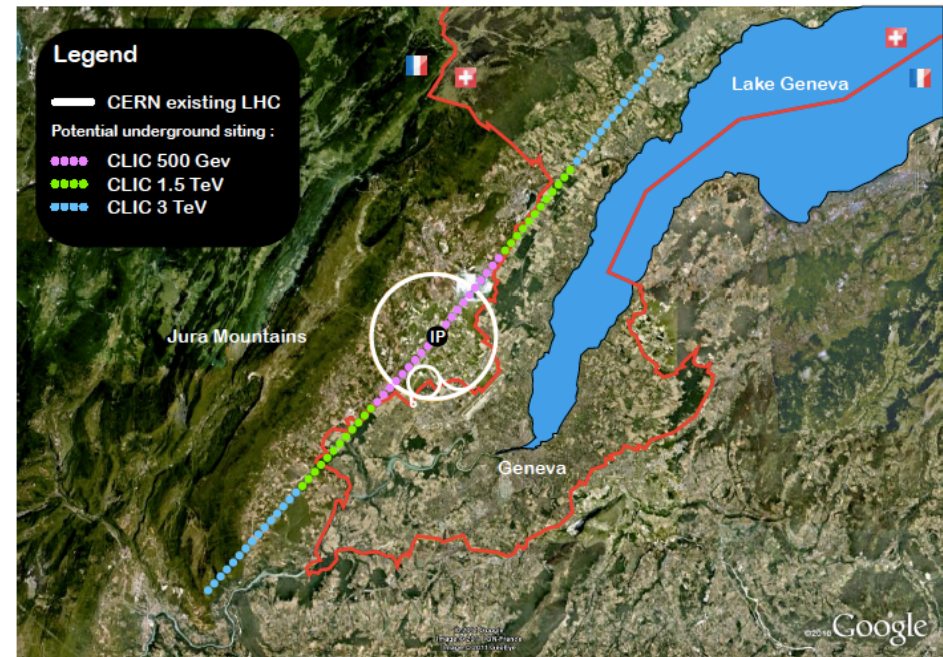


Fig. 7.2: CLIC footprints near CERN, showing various implementation stages [5].

CLIC physics potential



e^+e^- collisions at CLIC bring:

- Precision Higgs physics (SM and BSM), precision top physics
- Other precision physics, like WW scattering, single W production...
- Direct searches to weakly coupled BSM states, e.g. sleptons, gauginos
-

Physics highlights include

- Top, Higgs
- WW scattering, single W production
- SUSY
- Z' , contact interactions, extra dimensions, ...

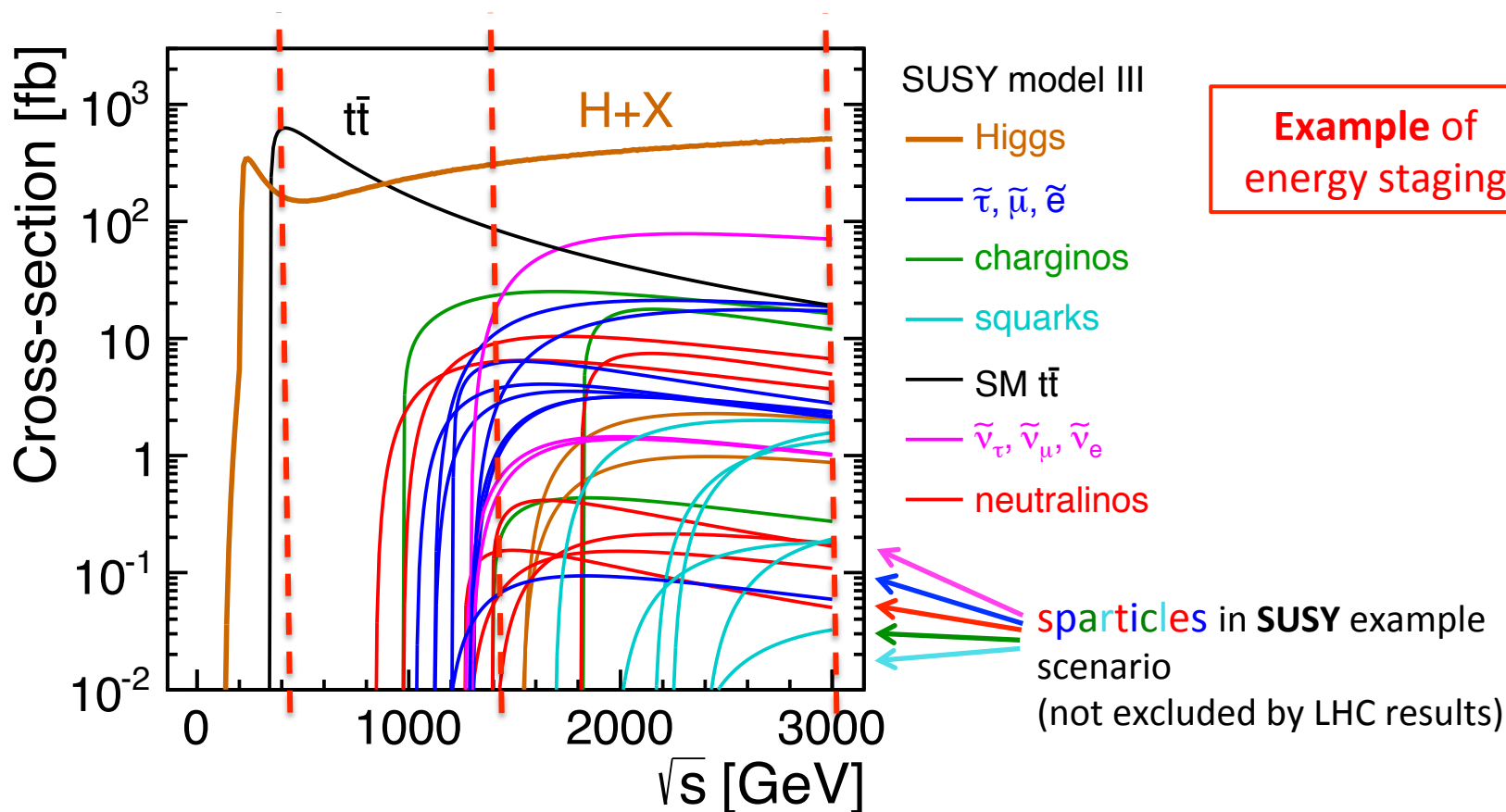
Experimental sensitivities are now **well understood**, most studies based on

- Full GEANT4 simulation/reconstruction
- Including pile-up of background

Disclaimer:

CLIC benchmark physics studies have (so far) concentrated on Higgs, top, SUSY, Z'
Plan to do more EW precision physics => will take longer than Snowmass time scale

- Precision SM measurements: Higgs, top $\rightarrow \sqrt{s} \lesssim 350$ GeV, and up to 3 TeV
- Discovery of new physics at TeV scale, unique sensitivity to particles with electroweak charge
- New Physics model discrimination, e.g. SUSY \rightarrow up to $\sqrt{s} \sim 3$ TeV



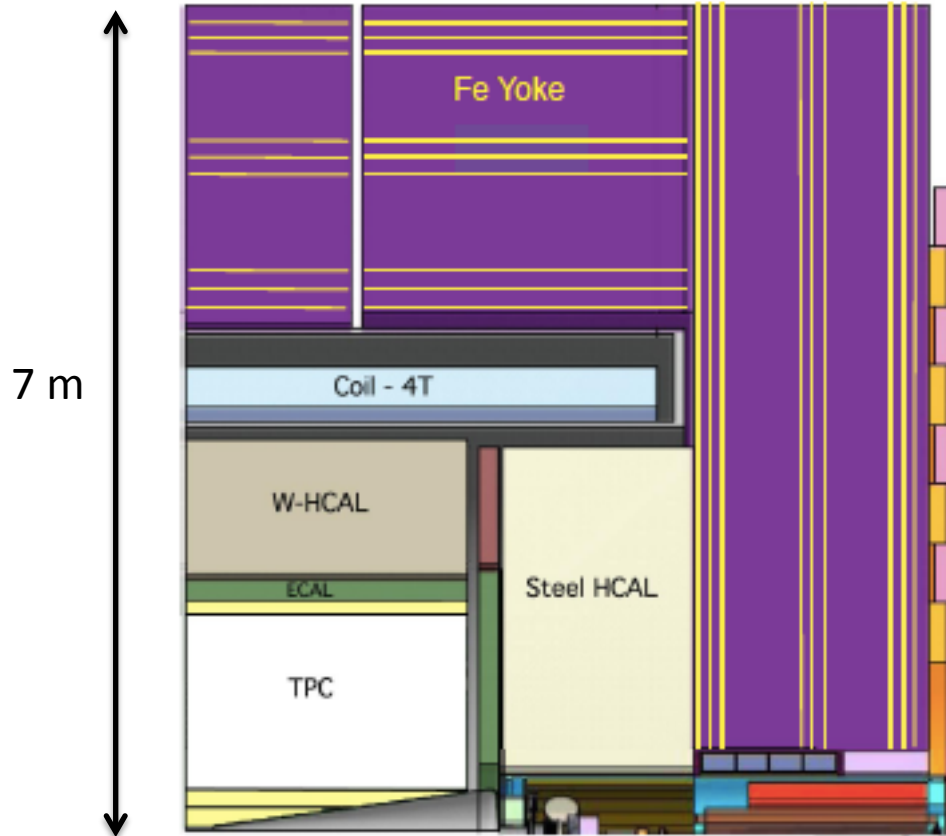
CLIC_ILD and CLIC_SiD



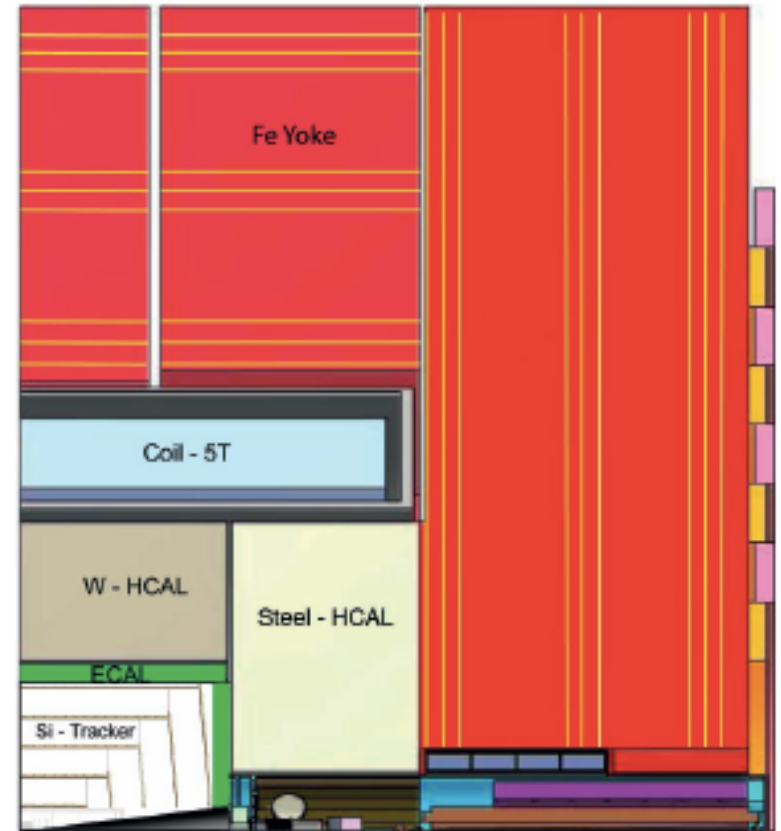
Two general-purpose CLIC detector concepts

Based on initial ILC concepts (ILD and SiD), adapted to CLIC conditions

CLIC_ILD



CLIC_SiD



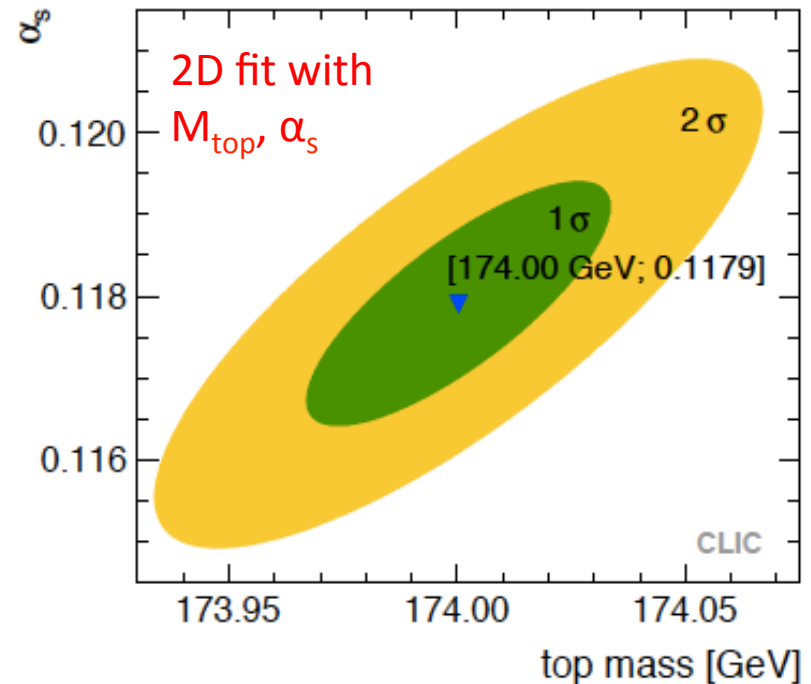
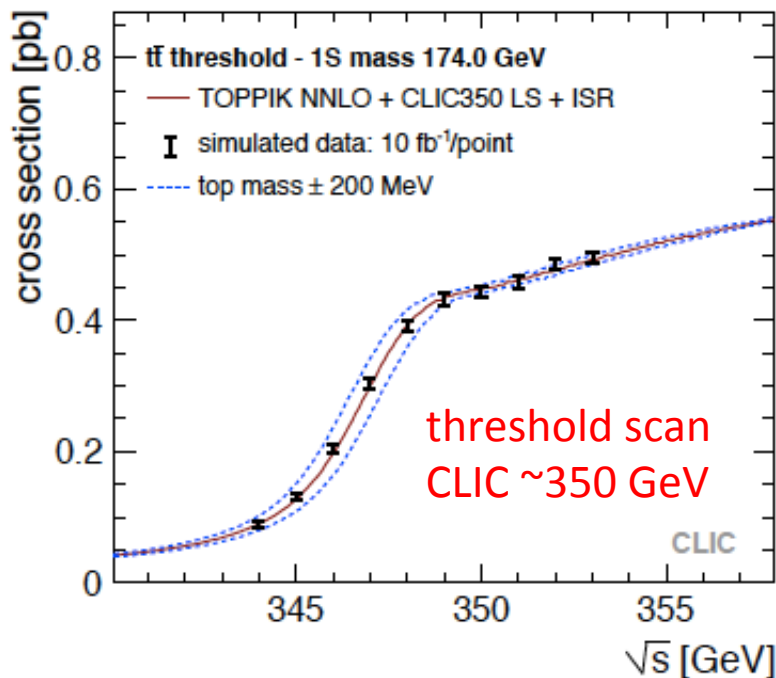
Most physics studies in this talk => full detector simulation + background overlays

Precision top physics 350, 500 GeV



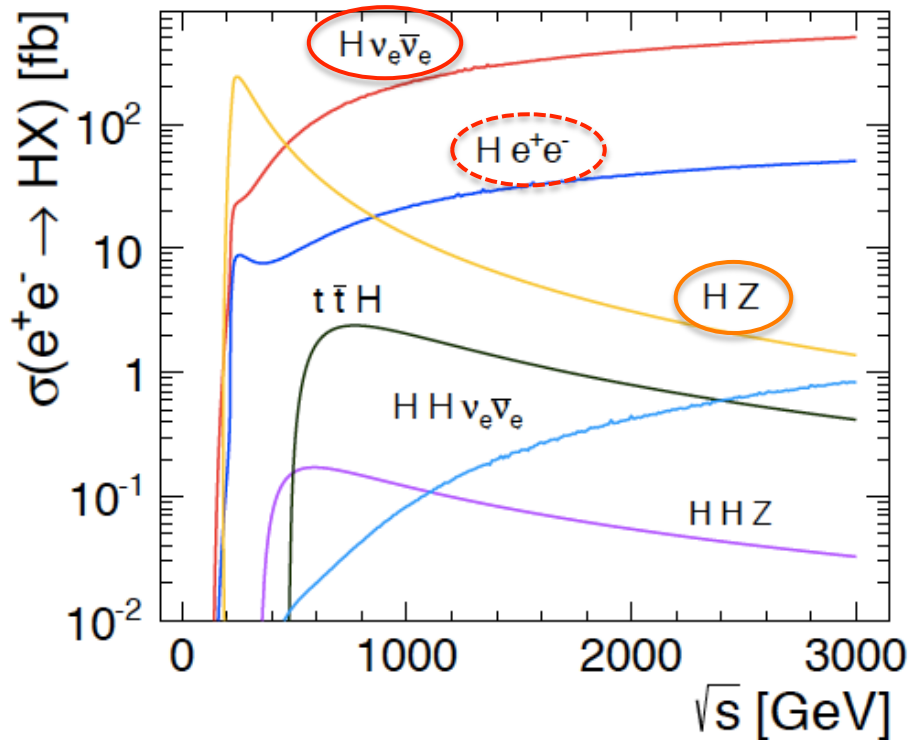
- e+e- collisions at and above the $t\bar{t}$ threshold provides two complementary ways of measuring the top quark mass:
 - **Direct reconstruction** (<= studied for CLIC at 500 GeV)
 - **Threshold scan** (<= studied for CLIC around 350 GeV)
- For both, total uncertainties on the level of 100 MeV are within reach with 100 fb^{-1} , highest precision (theoretically clean) with threshold scan

See: [arXiv:1303.3758](https://arxiv.org/abs/1303.3758)

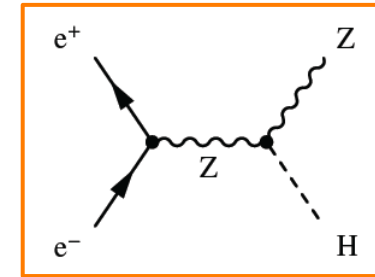


Other options for top physics at CLIC include: top couplings, LR asymmetries, boosted tops...

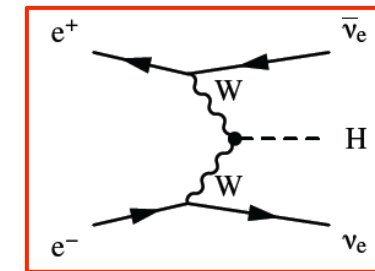
Higgs physics at CLIC



Dominant processes:



Higgsstrahlung
decreases with \sqrt{s}



W(Z) - fusion
increases with \sqrt{s}

Available luminosity increases with \sqrt{s} !

$M_h = 125$ GeV	350 GeV	1.5 TeV	3 TeV
$\sigma(e^+e^- \Rightarrow ZH)$	129 fb	6 fb	1 fb
$\sigma(e^+e^- \Rightarrow H\nu\nu)$	30 fb	309 fb	484 fb
Int \mathcal{L} (4-5 yrs)	500 fb ⁻¹	1.5 ab ⁻¹	2 ab ⁻¹
# ZH events	65000	7500	2000
# H $\nu\nu$ events	15000	460000	970000

Ongoing CLIC Higgs studies



- 350 GeV
 - σ of **HZ** - model-independent HZZ coupling
 - $\sigma \times \text{BR}$ of **bb, cc, gg, WW*, $\tau\tau$**
 - combined extraction of hadronic BRs
 - **Mass** and **$\sigma(\text{HZ})/\sigma(\text{H}\nu\nu)$** at 500 GeV
- 1.4 TeV
 - $\sigma \times \text{BR}$ of **bb, cc, gg, WW*, $\mu\mu, \gamma\gamma, Z\gamma, \tau\tau$**
 - **ZZ fusion** - ratio of HZZ and HWW couplings
 - combined fit of hadronic BRs, absolute coupling to W
 - σ of **ttH**
 - **self-coupling** (expecting improvement from further studies)
- 3 TeV
 - $\sigma \times \text{BR}$ of **bb, cc, $\mu\mu$**
 - **self-coupling** (expecting improvement from further studies)
 - potentially also **ZZ fusion**

already done

completion expected
by summer, including
a combined fit of
couplings

Higgs physics at CLIC



Benchmarking results obtained so far:

	Observable	stat. uncertainty
HZ	σ	4%
HZ	mass	120 MeV
$H \rightarrow \tau\tau$	$\sigma \times \text{BR}$	6.2%
HZ / $H\nu\nu$	σ/σ	5%
HZ, $H \rightarrow b\bar{b}$	mass	100 MeV
$H \rightarrow \tau\tau$	$\sigma \times \text{BR}$	3.7%
HH $\nu\nu$	self-coupling λ	30%
t \bar{t} H	σ	8%
$H \rightarrow b\bar{b}$	$\sigma \times \text{BR}$	0.2%
$H \rightarrow c\bar{c}$	$\sigma \times \text{BR}$	3.2%
$H \rightarrow \mu\mu$	$\sigma \times \text{BR}$	15%
HH $\nu\nu$	self-coupling λ	16%

350 GeV

500 GeV

1.4 TeV

<= estimate based on 1 TeV ILC result

3 TeV



All based on full detector simulation with beam-induced background and physics backgrounds
No polarisation assumed (80% electron polarisation will enhance $H\nu\nu$ /HH $\nu\nu$ signals by 80%)

Complete set of Higgs will be ready for Minneapolis meeting
(Incl. couplings to $b\bar{b}$, $c\bar{c}$, $g\bar{g}$, W^*W , Z^*Z , $\gamma\gamma$, γZ , $\tau\tau$, $\mu\mu$ and t \bar{t} H and self-coupling)

heavy Higgs, non-SM



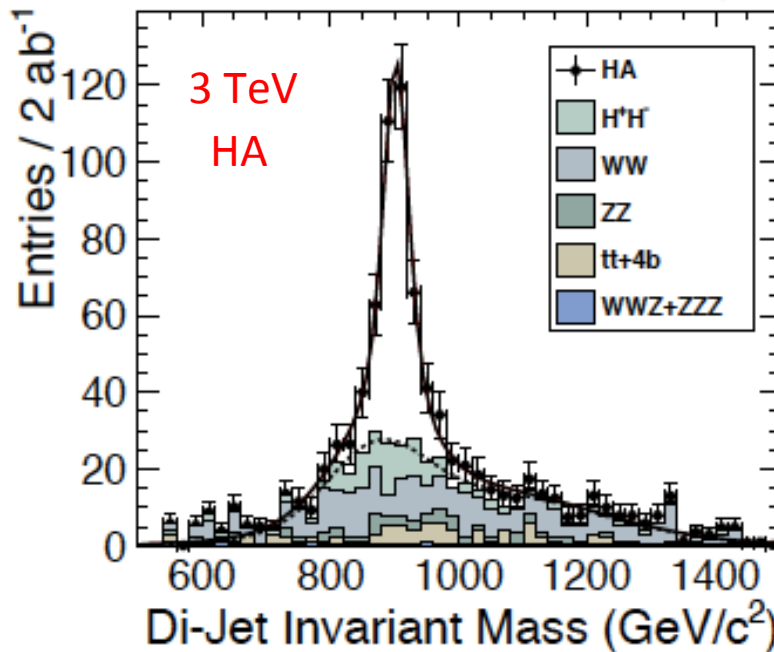
Higgs multiplet BSM → searches accessible up to $\sqrt{s}/2$

Example MSSM benchmark study at 3 TeV

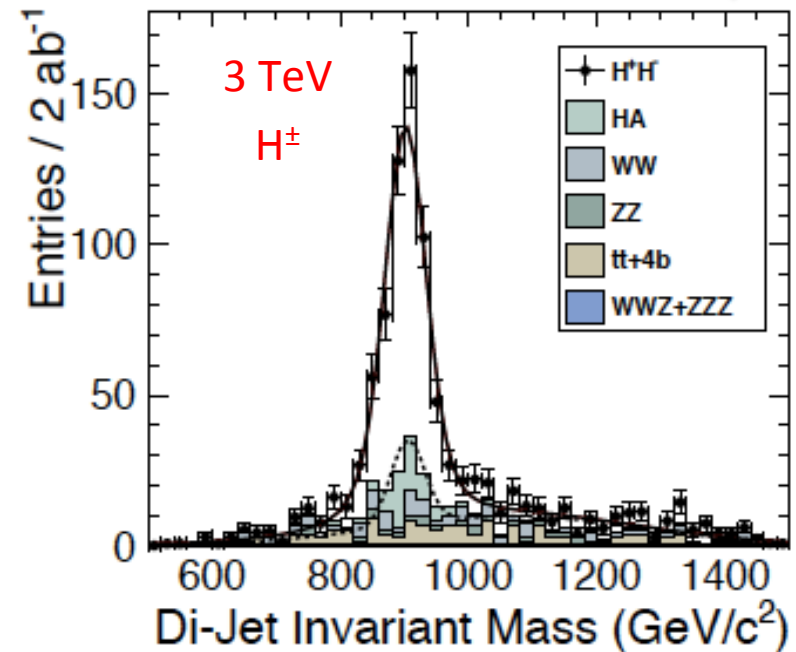
Multi-jet final states

Full simulation studies with background overlay

$m_{A^0/H^0} : \pm 2.8 \text{ GeV} \downarrow$

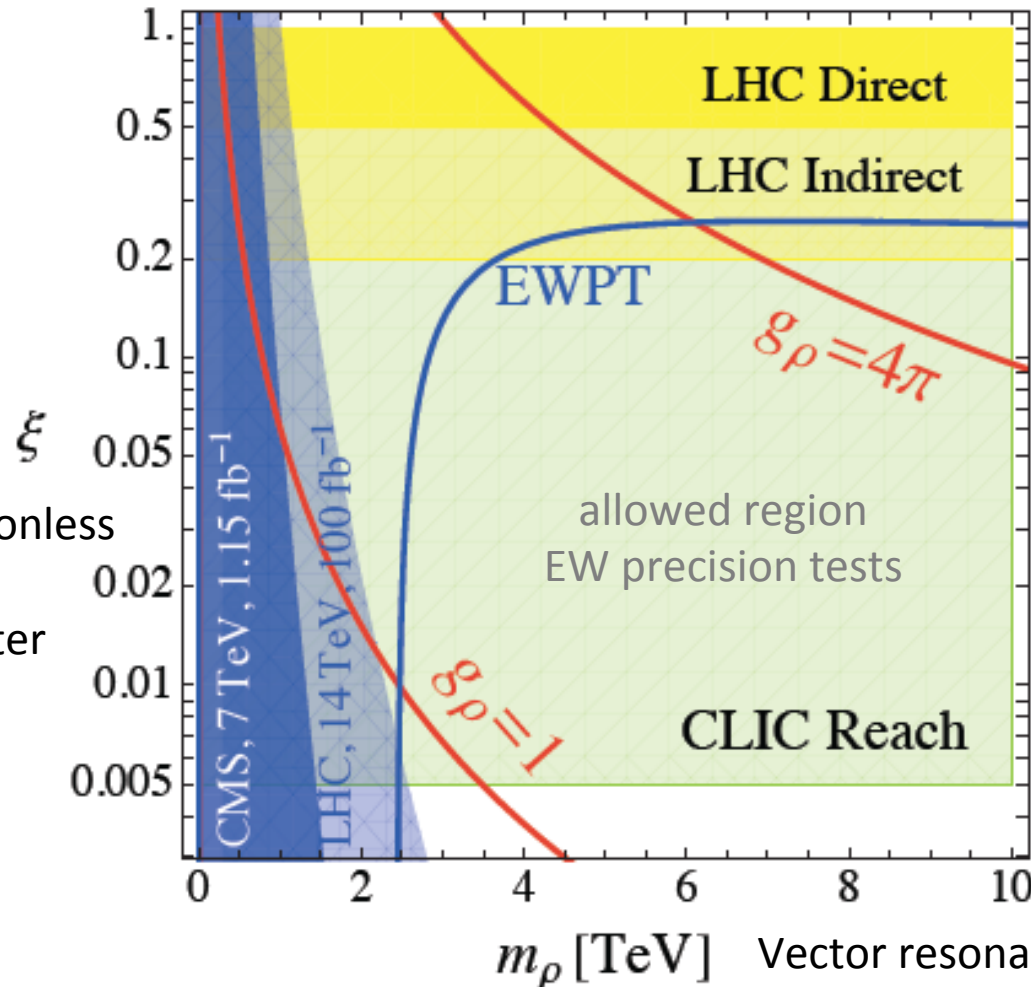


$m_{H^\pm} : \pm 2.4 \text{ GeV} \downarrow$



$M_1 = 780 \text{ GeV}, M_2 = 940 \text{ GeV}, M_3 = 540 \text{ GeV}$
 $A_0 = -750 \text{ GeV}, m_0 = 303 \text{ GeV}, \tan\beta = 24, \mu > 0$
 $m_t = 173.3 \text{ GeV}, M_b(M_b) = 4.25 \text{ GeV}, \alpha_s(M_Z) = 0.118$

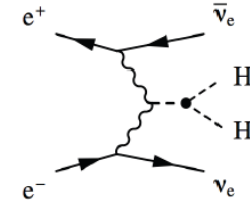
Higgs compositeness



LHC: WW scattering and strong double Higgs production

LHC: single Higgs processes

CLIC: double Higgs production via vector boson fusion



LHC: direct search $WZ \Rightarrow 3$ leptons

Allows to probe Higgs compositeness at the 30 TeV scale for 1 ab⁻¹ at 3 TeV
(60 TeV scale if combined with single Higgs production)

WW and single W production



These are exciting physics studies, that are still to be done for CLIC
Cross sections are large => **millions of events**

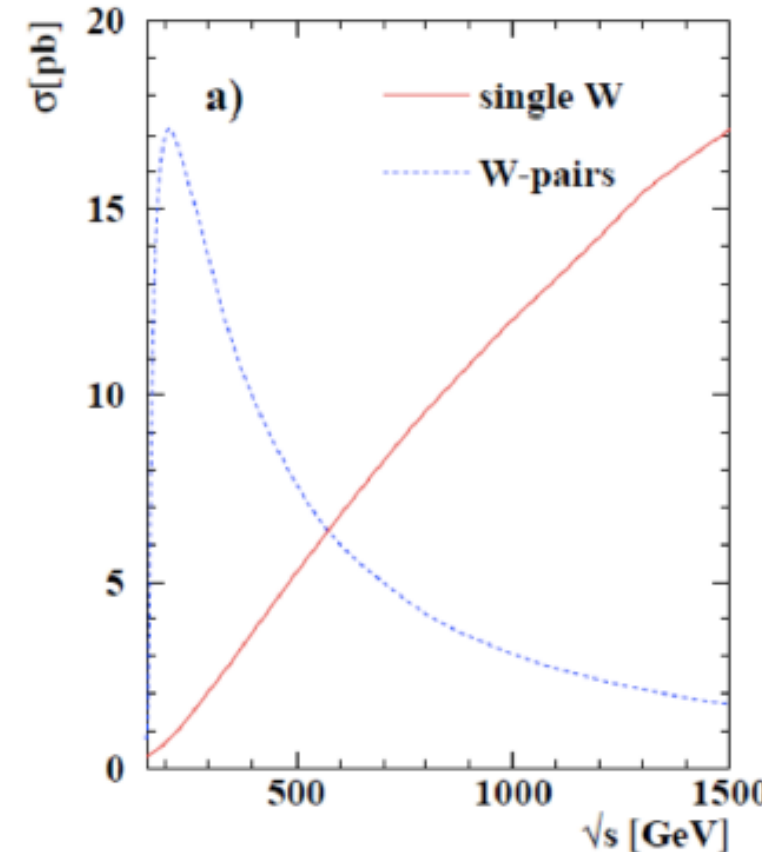
$e^+e^- \rightarrow WW$

more favourable at the lower CLIC energies

$e^+e^- \rightarrow W\text{e}\nu$

more favourable at the higher CLIC energies

See talk G. Wilson



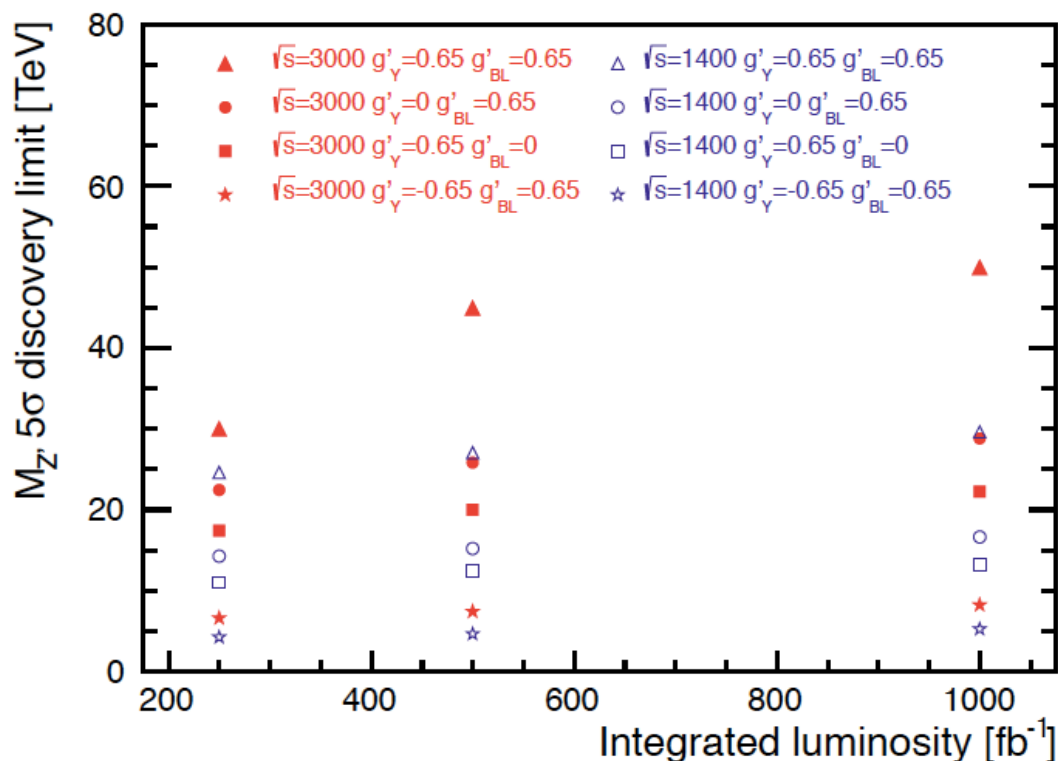
Only study done so far:

Successful use of single W production for measurement of polarisation at the interaction point at 3 TeV => $\ll 1\%$ precision achieved

sensitivity to Z'



Example: neutral gauge boson (Z') in minimal anomaly-free Z' model (AF Z')



Dimuon events
3 TeV
1.4 TeV

$M_{Z'}$ 5σ discovery limit as function of the integrated luminosity for different values of the couplings g'_Y and g'_{BL} . The limits shown are determined from the combined observables $\sigma + A_{FB}$ at 3 TeV and 1.4 TeV.

Study of Z' 5σ discovery potential in at 1.4 TeV and 3 TeV, for different coupling values

contact interactions

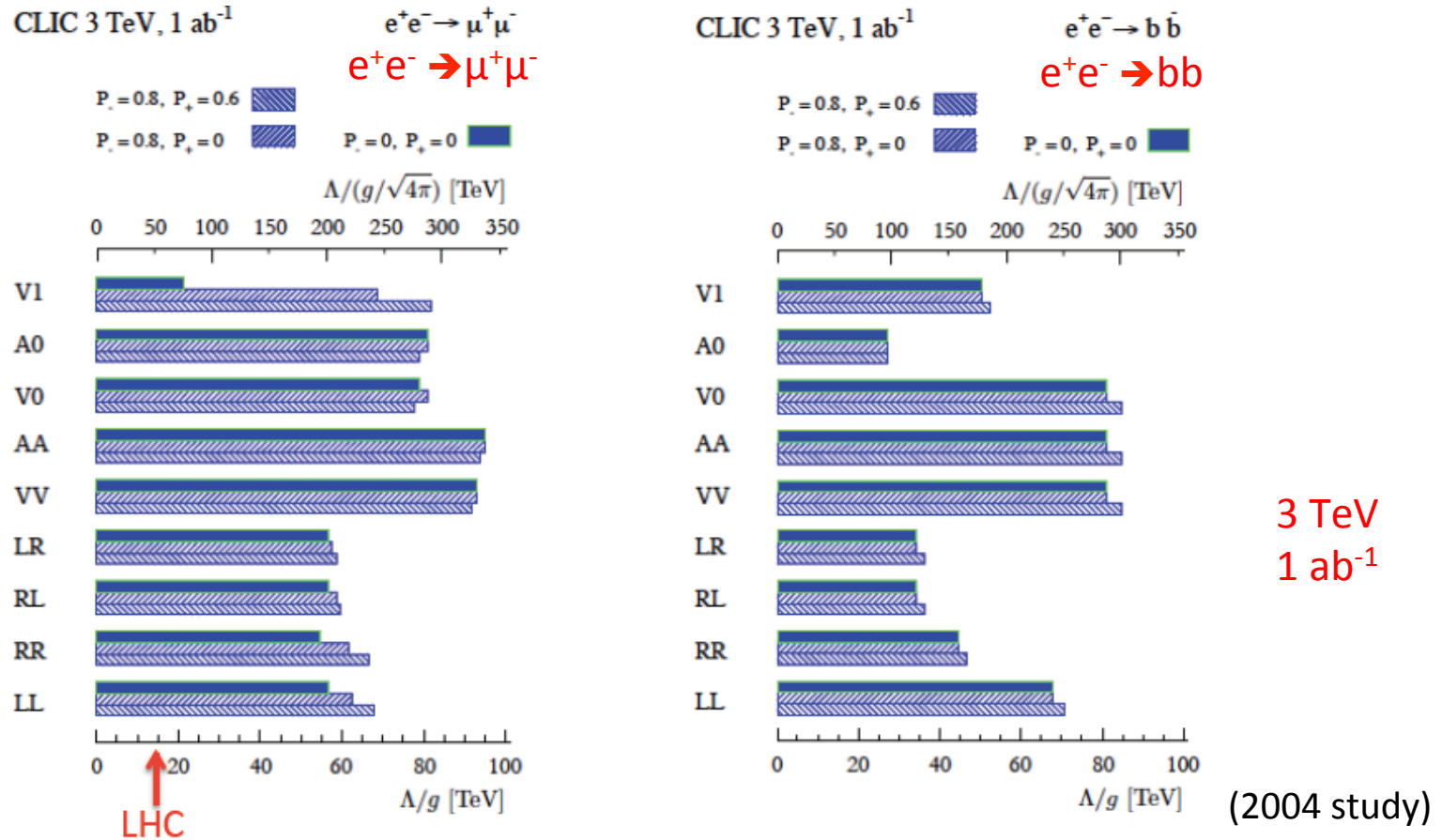


Fig. 1.14: Limits on the scale of contact interactions (Λ/g) that can be set by CLIC in the $\mu^+\mu^-$ (left) and $b\bar{b}$ (right) channels with $\sqrt{s} = 3$ TeV and $\mathcal{L} = 1$ ab⁻¹. A degree of polarisation $P_- = 0, 0.8$ ($P_+ = 0, 0.6$) has been assumed for the electrons (positrons). The various models are defined in Table 6.6 of [20], except the model V1 which is defined as $\{\eta_{LL} = \pm, \eta_{RR} = \mp, \eta_{LR} = 0, \eta_{RL} = 0\}$.

Limits on the scale (Λ/g) of contact interactions

CLIC physics reach, short overview



These were just some examples of CLIC physics

- more details given in Vol. 2 & 3 of CLIC CDR

Challenge the Standard Model with **direct measurements** and at the **loop level**

- Challenge SM up to the 60 TeV scale

New particle	CLIC3 1 ab^{-1}	
squarks [TeV]	1.5	Direct observation
sleptons [TeV]	1.5	
Z' (SM couplings) [TeV]	20	
2 extra dims M_D [TeV]	20-30	Loop / effective operator
TGC (95%) (λ_γ coupling)	0.0001	
μ contact scale [TeV]	60	
Higgs compos. scale [TeV]	60	

CLIC
3 TeV

CLIC detector and physics study organisation



Pre-collaboration structure, based on a “Memorandum on Cooperation”
<http://lcd.web.cern.ch/LCD/Home/MoC.html>



Australia: ACAS; Belarus: NC PHEP Minsk; Czech Republic: Academy of Sciences Prague; Denmark: Aarhus Univ.; Germany: MPI Munich; Israel: Tel Aviv Univ.; Norway: Bergen Univ.; Poland: Cracow AGH + Cracow Niewodniczanski Inst.; Romania: Inst. of Space Science; Serbia: Vinca Inst. Belgrade; Spain: Spanish LC network; UK: Birmingham Univ. + Cambridge Univ. + Oxford Univ.; USA: Argonne lab; + CERN

summary and outlook



CLIC Physics:

- Complementary to the LHC
- Focus on high precision measurements
- Physics precision capabilities demonstrated (full simulation with pile-up)
- Staged approach => large potential for SM and BSM physics

~350 – 375 GeV : precision Higgs and top physics

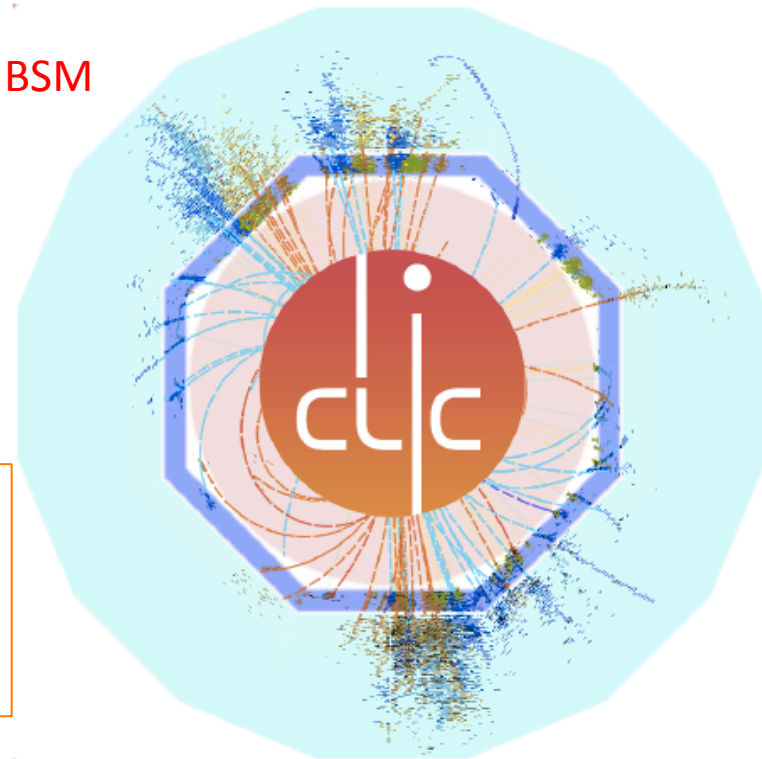
~1.5 TeV : Higgs (including ttH and self-coupling), BSM

~3 TeV : Higgs, Higgs self-coupling, BSM, ...

Ongoing CLIC physics potential studies

- current focus on detailed Higgs studies
- more on EW precision on a ≥ 1 year timescale

**CLIC is an exciting and realistic option for
a future machine at the energy frontier
Welcome to join !**



lcd.web.cern.ch/lcd/

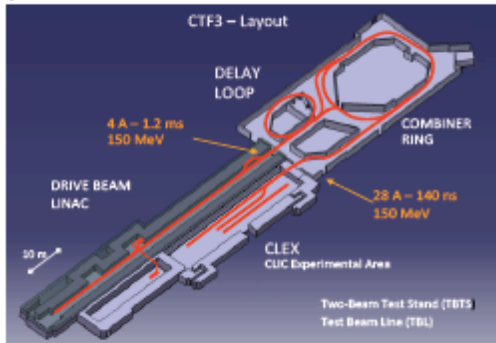
SPARE SLIDES

CLIC strategy and objectives



2012-16 Development Phase

Develop a Project Plan for a staged implementation in agreement with LHC findings; further technical developments with industry, performance studies for accelerator parts and systems, as well as for detectors.



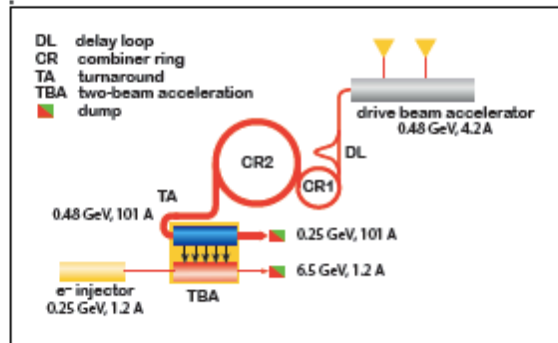
2016-17 Decisions

On the basis of LHC data and Project Plans (for CLIC and other potential projects), take decisions about next project(s) at the Energy Frontier.

2017-22 Preparation Phase

Finalise implementation parameters, Drive Beam Facility and other system verifications, site authorisation and preparation for industrial procurement.

Prepare detailed Technical Proposals for the detector-systems.



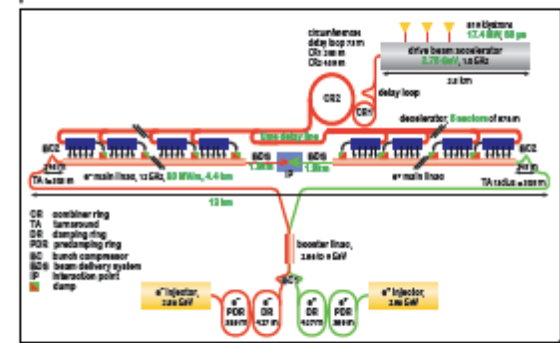
2022-23 Construction Start

Ready for full construction and main tunnel excavation.

2023-2030 Construction Phase

Stage 1 construction of a 500 GeV CLIC, in parallel with detector construction.

Preparation for implementation of further stages.



2030 Commissioning

From 2030, becoming ready for data-taking as the LHC programme reaches completion.

Faster implementation possible, (e.g. for lower-energy Higgs factory): **klystron-based initial stage**

plans for the phase 2013-2016



Further exploration of the physics potential

- Complete picture of Higgs prospects at ~ 350 GeV, ~ 1.4 TeV, ~ 3 TeV
- Discovery reach for BSM physics
- Sensitivity to BSM through high-precision measurements

cf. LHC results



Drives the CLIC staging strategy

Detector Optimisation studies

- Optimisation studies linked to physics (e.g aspect ratio, forward region coverage);
- Interplay between occupancies and reconstruction;
- Interplay between technology R&D and simulation models.

Technology demonstrators

- Many common developments with ILC
- Complemented with CLIC requirements



integrated luminosity

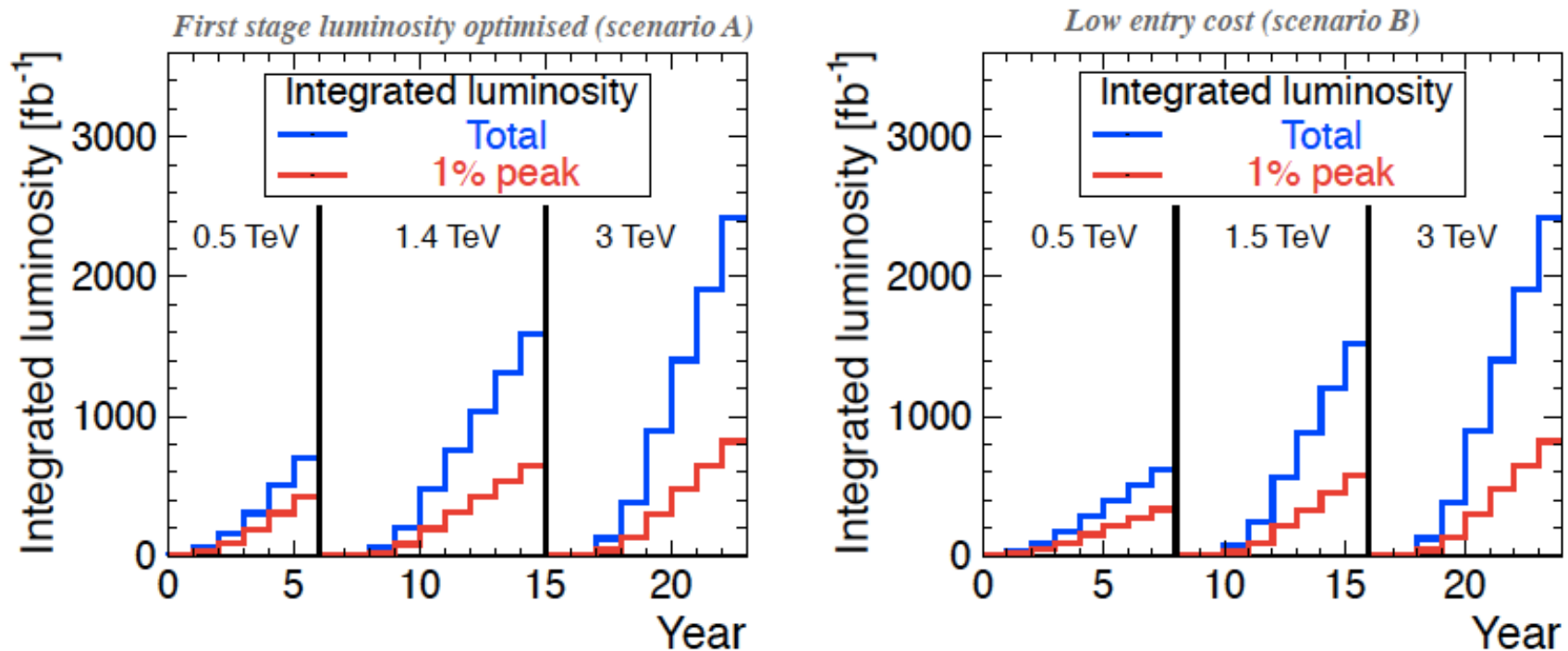


Fig. 5.2: Integrated luminosity in the scenarios optimised for luminosity in the first energy stage (left) and optimised for entry costs (right). Years are counted from the start of beam commissioning. These figures include luminosity ramp-up of four years (5%, 25%, 50%, 75%) in the first stage and two years (25%, 50%) in subsequent stages.

Based on 200 days/year at 50% efficiency (accelerator + data taking combined)

CLIC detector concepts



... in a few words ...

